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Concentrator and Space Applications of High-Efficiency Solar Cells – Recent Developments

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Abstract. GaInP/GaAs cells invented and developed at NREL have achieved world-record efficiencies. We estimate that their production for space applications has grown to > $100 million/yr. Approximately 300 MW/yr of 1000X terrestrial concentrator cells could be fabricated with the existing manufacturing capacity at a cost of about 21¢/Wp. A resurgence of interest in terrestrial PV concentrators, together with the strength of the III-V space-solar-cell industry, indicate that III-V cells are also attractive for terrestrial applications.

INTRODUCTION

The two-junction (cascade) $Ga_{0.5}In_{0.5}P$/GaAs cell was invented in November 1984 at the National Renewable Energy Laboratory (NREL) (1) (see Fig. 1). Over the next few years, the growth and basic properties of $Ga_{0.5}In_{0.5}P$ (hereafter, GaInP) were studied. As the purity of the source materials was improved and the device optimized, the efficiencies climbed: 4% in 1985 (2), 10% in 1987 (3), 21.8% in 1988 (4), and 27.3% in 1990 (5). When the two-junction efficiencies passed the efficiency of single-junction GaAs, the cascade cell became attractive for space applications. The cascade cells provide a higher efficiency, lower temperature coefficient, improved radiation resistance, and reduced series-resistance losses, and they were recognized with an R&D100 Award in 1991.

In 1994, world-record efficiencies were reported, 29.5%, 25.7%, and 30.2% under AM1.5 global, AM0, and AM1.5 direct (150-200X), respectively (6,7). Although the cascade cell requires carefully controlled growth of more than a dozen layers, NREL's work was quickly duplicated. Japan Energy Corporation, Spectrolab, and Applied Solar Energy Corporation (ASEC, currently TECSTAR) all reported cells with respectable efficiencies in 1994 (8-10). By 1996, ASEC reported manufacturing experience with the cascade cells (11), and Spectrolab reported growth of triple-junction cells (12).

In the two years since the last U.S. PV Review meeting, the GaInP/GaAs cell has been received very enthusiastically by the space PV community. The manufacturing and usage experience that accompanies the large space-PV production volumes is going a long way toward providing the terrestrial concentrator industry with a source of high-efficiency, low-cost concentrator cells. Although it has not yet achieved a significant production level, the concentrator industry is progressing by installing new systems, developing new products, and working to establish standards for qualification testing. This paper describes recent advances in both the III-V and concentrator industries and discusses why these imply that III-V cells are attractive for terrestrial applications.

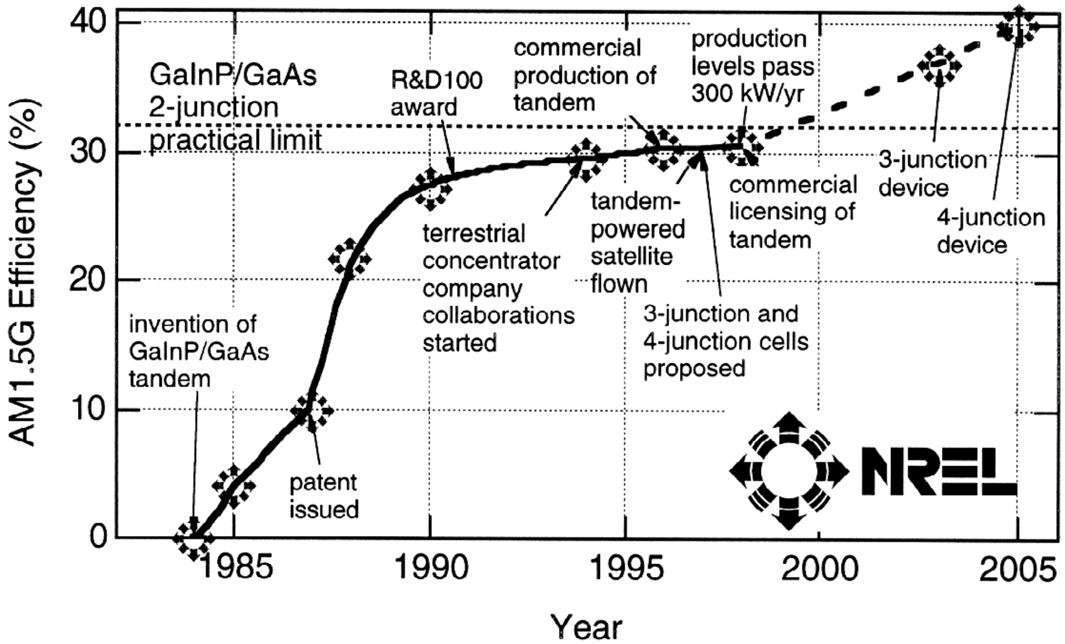

FIGURE 1. History (efficiency records, indicated by *) and future projections for high-efficiency GaInP/GaAs cells.

RECENT DEVELOPMENTS

Recent Developments in Manufacturing of GaInP/GaAs Cells

With the help of the ManTech Program sponsored by the Air Force and NASA, the efficiencies and production volumes of GaInP/GaAs cascade cells grown on Ge substrates have continued to climb (13-14). The addition of an active Ge junction, formed during the growth, pushed the best-cell AM0 efficiencies to 25.76% and 24.7% at Spectrolab and TECSTAR, respectively (13). The first commercial satellite with GaInP/GaAs cells was built by Spectrolab/Hughes and launched in August 1997 (15).

Over the last few years, production of III-V cells for use in space has increased dramatically (see Fig. 2). The current production capacity of III-V cells at TECSTAR is 350 kW/yr. Although most of TECSTAR's III-V production is single-junction cells, by the end of 1999 TECSTAR expects to convert all of its III-V production to cascade cells and increase production capacity to 520 kW/yr. Spectrolab is manufacturing the multijunction cells at a rate of 325 kW/yr, with 210 kW already delivered (15). If the sale price is $300/W, the *total current production capacity of GaInP/GaAs cells is > $100 million/year, with about $100 million worth already delivered.* This is especially impressive because production just began in 1996.

In the spring of this year, TECSTAR and NREL signed a licensing agreement giving TECSTAR non-exclusive rights to manufacture GaInP/GaAs space cells. Others have also expressed an interest in licensing the technology.

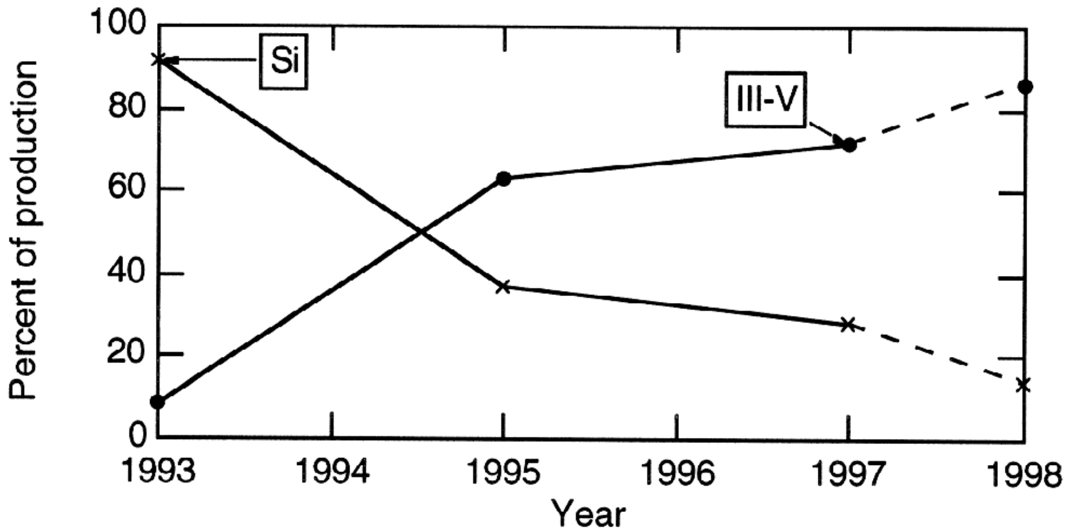

FIGURE 2. Distribution of TECSTAR production between Si and III-V, reflecting an increase in production of close to a factor of 10. Data courtesy of TECSTAR.

III-V Space-Cell Production Makes Terrestrial Applications Attractive

The current production capacity of about 700 kW/yr of III-V cells for space would correspond to about 700 MWp/yr if the same cells were used at 1000X for terrestrial concentrator systems. This is roughly five times the total 1997 terrestrial PV sales. If the PV industry is to grow fast enough to supply a significant fraction of the world's energy 10-15 years from now, the industry may need to use concentrator systems.

The mass production of III-V devices has reduced the cost of III-V epitaxy. A recent EMCORE study showed that, at 90% yield and 10 μm/h growth rate, a 4-in. Ge wafer with a GaInP/GaAs cell grown on it costs $210 (16). If 90% of the 4-in. wafer can be used to make 26% 1000X concentrator cells, the cell cost would be 21¢/Wp. (This assumes 90% optical efficiency, 850 W/m^2 irradiance, 10% area used for busbars, and that 25% of the cost is in processing.) Current prices for concentrator III-V cells can be expected to be at least 10 times this, largely because making the concentrator cells is a research project. These cells may be even more attractive for concentrator systems when the efficiencies are pushed higher with 3- and 4-junction concepts (17).

Recent Developments in the Terrestrial Concentrator Industry

BP Solar has almost completed a 0.5 MWp system in Tenerife. This system uses reflective troughs with a concentration of 32X and BP Solar laser-groove buried grid 19%-efficient silicon cells. The cost of electricity generated by the EUCLIDES concept is estimated at 12¢/kWh compared with 22¢/kWh for a flat-plate module (18).

In April 1998, Honda (19) unveiled a prototype 270X concentrator system using SunPower 26%-efficient Si cells (see Fig. 3). Although Honda has not yet announced any plans for commercializing the concentrator system, the April report indicated that "Honda plans to launch the system for personal residential uses in the future."

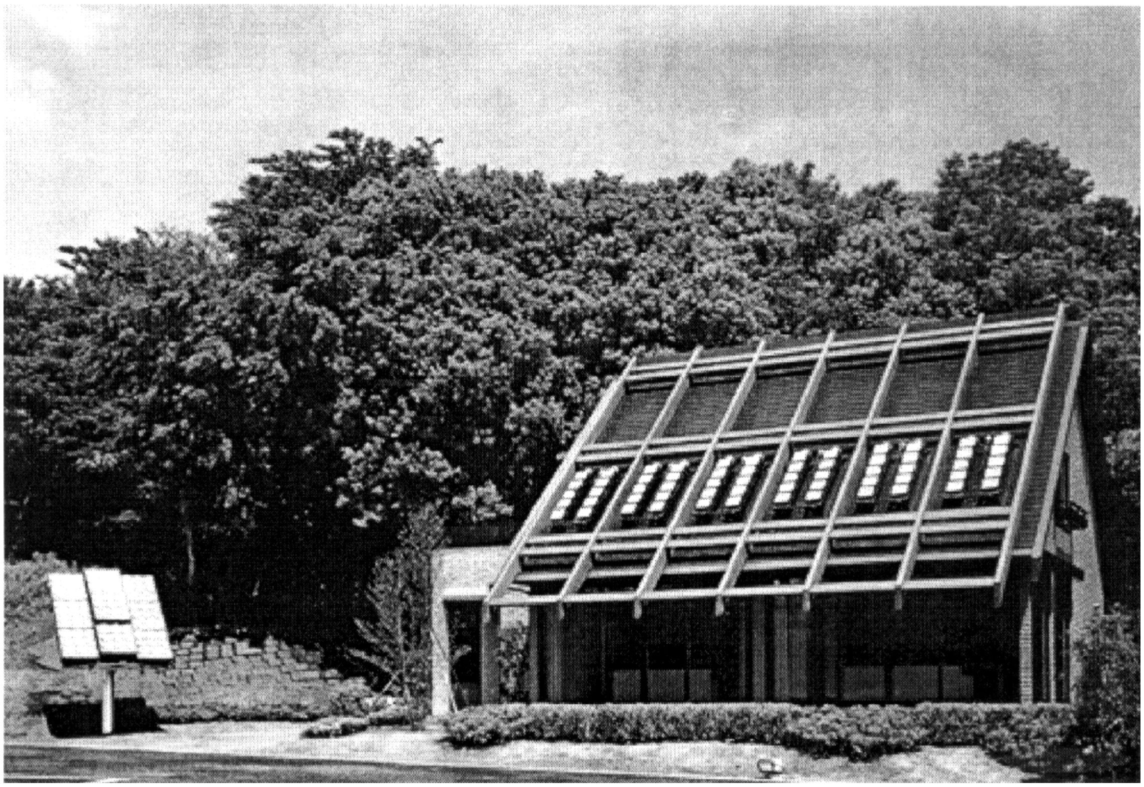

FIGURE 3. Honda prototype systems installed on top of and next to a house.

SunPower is also working with a number of other companies and expects total orders in 1999 of more than 1 MWp of concentrator cells.

Amonix has installed a number of systems in the past year and is planning to install an additional 100 kWp by the end of the first quarter of 1999. These systems are being made on a 1 MWp/yr production line, reducing costs significantly.

SAIC is considering use of PV concentrator systems as an alternative to Stirling engines. High-efficiency silicon cells like those made at SunPower and Amonix could be used in the SAIC dish in the short term. High-voltage III-V multijunction cells are also being investigated for this sort of application (20). SAIC has estimated the capital cost of a 1000 MWp/yr dish/PV plant at $7 million ($5 million for the dish factory and $2 million for the solar-cell plant), compared with an estimated $125 million for a 1000 MWp/yr crystalline-silicon production facility (21).

In Europe, the JOULE program has funded a number of projects in addition to EUCLIDES. At the University of Reading, ninety concentrator concepts using 40X or less were compared (22), and the best four were fabricated and tested (23,24). A study by the University of Ulster and BP Solar evaluated a static, low-concentration design appropriate for building integration and concluded that 95% of the electrical output of a flat-plate system could be obtained with only 40% of the silicon (25). Static, low-concentration systems have been shown elsewhere to be cost effective (26). Carefully designed, small-volume, non-imaging optics can achieve 200X, with an acceptance angle as large as 4.7° and an average thickness-to-diameter ratio of only 0.48 (27).

As the prospects for increased sales of terrestrial concentrator systems increase, both the concentrator and cell-manufacturing companies have expressed an interest in using multijunction III-V cells in terrestrial concentrator systems. In the past year, three proposals by private companies were submitted to various funding agencies requesting funding to develop III-V cells for terrestrial concentrator applications.

A common perception today is that the PV market will be dominated by building-integrated applications and that concentrator PV cannot compete for these markets. However, concentrator systems *can* be building integrated, as discussed above. Although many customers may choose a product without moving parts, creatively designed concentrator systems will be able to capture a share of the building-integrated PV market.

Standards Development Provides Foundation for Industry

In the past year, significant progress has been made toward developing standards for concentrator systems. NREL has coordinated the writing of IEEE Recommended Practice for the Qualification of Photovoltaic Concentrator Modules (28). The first modules will start through this test sequence in late 1998. The International Electrotechnical Commission will sponsor the development of a similar international standard (29). Sandia National Labs is coordinating an effort to write a test procedure for sun trackers (for both flat-plate and concentrator modules) (30). Many failures of concentrator modules have been linked to tracker problems (31), implying that this test procedure may be key toward improving concentrator-module performance.

In general, healthy growth of any industry requires carefully designed standards. Today's concentrator systems, strictly speaking, should all be viewed as prototypes. Because the qualification test procedure is not yet completed, no concentrator system has yet been qualified. Some concentrator modules were tested at Sandia, but the tests were not complete. In the days before an adequate qualification test was designed, flat-plate modules also suffered failures. The failure rate dropped significantly for modules that passed the carefully designed qualification test. Similar improvements in concentrator module reliability can be expected when fielded systems have all passed an adequate qualification test.

SUMMARY

NREL’s GaInP/GaAs cells have been enthusiastically accepted by the space PV industry because of their high efficiency, low temperature coefficient, and good radiation resistance, and are now being manufactured at 325 kW/yr by Spectrolab. TECSTAR has a III-V cell production capacity of 350 kW/yr and anticipates using all of that for GaInP/GaAs cells by the end of 1999. This large manufacturing base has allowed the manufacturing costs to drop, to about 21¢/Wp for 1000X concentrator cells. Costs are continuing to drop, and efficiencies may improve dramatically with new 3- or 4-junction concepts. Concentrator arrays using III-V cells are scheduled to fly on upcoming NASA missions (see Appendix). The advances of concentrators for space applications are paralleled by advances of the terrestrial concentrator industry. BP Solar is bringing a 0.5 MWp system on line this fall, and Honda has unveiled a prototype of a concentrator system that can be roof-mounted. The development of qualification standards for concentrator systems is progressing well and is expected to help the industry in fielding reliable products. The sum of these recent developments, perhaps insignificant when isolated, point to a resurgence of interest in terrestrial PV concentrators as a strong option to become a significant future-generation PV technology.

APPENDIX

Recent Developments of PV Concentrators in Space

One of the current trends in space PV (32) is the use of concentrators. III-V cells are an obvious choice for concentrator systems because of their high efficiency, high voltage (low current), and low temperature coefficients. The potential advantages of concentrator arrays in space include improved radiation resistance, lower cost, higher efficiency, and a reduced capital investment for expansion of production capacity. Although there has been reluctance to use concentrator arrays in space because of their need to be accurately pointed at the sun, space concentrator technology is being pushed very hard by a number of organizations.

Popular Science recently featured NASA's Deep Space 1 (DS1) mission on its cover (33). DS1 is scheduled to launch in October 1998 and will not only fly past an asteroid and a comet, but will also be testing a dozen new cutting-edge technologies. The solar concentrator arrays are one of the new technologies, and, because they produce 50% more power per area than conventional arrays, they enable NASA to include another new, energy-hungry technology: ion propulsion. The development of these concentrator arrays was sponsored by the Ballistic Missile Defense Organization. Able Engineering assembled the arrays using TECSTAR-manufactured GaInP/GaAs cells and linear-focus lenses designed by ENTECH, Inc. (34,35).

Concentrator solar arrays will be used to provide a portion of the electrical power for NASA's Wide Field Infrared Explorer mission and the Air Force's MightySat mission (36). In February, Spire Corporation completed a prototype panel using Spire's high-efficiency GaAs space solar cells in lightweight concentrator array panels built by Composite Optics, Inc. Lightweight mirrors focus sunlight onto the cells, thus reducing the cost of the array. The need to maintain high pointing accuracy toward the sun is minimized by using a concentration ratio of less than three.

The National Reconnaissance Office has funded the development of graded-index solar concentrators. This work, done by the United Innovations Division of DR Technologies, Inc., uses both a reflector and a graded-index lens to focus the light to 50X on GaInP/GaAs cells (37).

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